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THE ROLES OF JETS: CF, CCSN, PN, CEE, GEE, ILOT

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Abstract. I review the roles of jet-inflated bubbles in determining the evolution of different astrophysical objects. I discuss astrophysical systems where jets are known to inflate bubbles (cooling flow [CF] clusters; young galaxies; intermediate luminosity optical transients [ILOTs]; bipolar planetary nebulae [PNe]), and systems that are speculated to have jet-inflated bubbles (core collapse supernovae [CCSNe]; common envelope evolution [CEE]; grazing envelope evolution [GEE]). The jets in many of these cases act through a negative jet feedback mechanism (JFM). I discuss the outcomes when the JFM fizzle, or does not work at all. According to this perspective, some very interesting and energetic events owe their existence to the failure of the JFM, including stellar black holes, gamma ray bursts, and type Ia supernovae.

1 Introduction

In many astrophysical objects jets play significant roles in the evolution. In the present study it is assumed that when ever an accretion disk (or a belt) with a sufficiently high accretion rate is formed, two opposite jets are launched.

In section 2 I list several groups of astrophysical objects where bubbles and lobes are inflated by jets. This is an updated version of the list presented by Soker *et al.* (2013). I do not list objects where jets typically do not inflate bubbles. These objects include young stellar objects and some elliptical planetary nebulae (PNe), both of which are old members of astrophysical objects with jets, and the recently proposed group of Type Ia supernova remnants (Tsebrenko & Soker 2013).

In some of the above listed objects with jet-inflated bubbles, the operation of the jets is regulated by a negative jet feedback mechanism (JFM). In section 3 I list those objects and some of their properties that are related to the JFM. I then discuss and speculate on the outcomes when the JFM fizzle at early times, or does not work at all. In this 4-pages-limited paper I only present the fizzle-outcomes; a more extended discussion will be presented elsewhere.

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Table 1. Properties of jet-inflated bubbles

	Clusters CFs	Young galaxies	CCSNe	Bipolar PNe	CEE	GEE	ILOTs
Energy (erg)	10^{60}	10^{59}	10^{51}	10^{44}	10^{44-48}	10^{44-48}	10^{44-50}
Mass ($M_\odot$)	10^{12}	10^{11}	10	1	1	1	1-100
Size	100 kpc	10 kpc	10^9 cm	0.1 pc	$10^{1-2} R_\odot$	$10^{1-2} R_\odot$	$10^{1-2} R_\odot$
Time	10^{7-8} yr	10^{7-8} yr	$1-3$ s	10^{1-2} yr	1 yr	100 yr	days-yrs
$T_{\rm bubble}(K)$	10^{9-10}	10^{9-10}	10^{10}	10^6	10^{7-9}	10^{7-9}	10^{6-8}
$T_{\rm res}(K)$	10^{7-8}	10^{6-7}	few$\times 10^9$	10^4	10^{5-6}	10^5	10^{4-6}
Accretor	SMBH	SMBH	NS/BH	MS/WD	MS/WD/NS	MS/NS	
M_a ($M_\odot$)	10^{8-10}	10^{6-9}	$1-5$	1	1	1	1-50
Jets' main effects	Heating ICM	Expelling gas	Exploding the star	Shaping lobes	Ejecting envelope	Ejecting outer envelope	Shaping; radiation
Observation	X-ray bubbles	Massive outflows		Bipolar PNs			Bipolar LBVs

Properties of systems where jet-inflated bubbles are observed or assumed to exist. The different listed values are typical and to an order or magnitude (or two even) accuracy only. The quantities given are as follows. Energy in one jets-launching episode; system mass; size of the relevant ambient gas; duration of the jets activity episode; temperature of the gas inside the bubble; temperature of the ambient gas (the subscript ‘res’ stands for reservoir of gas for accretion); the accreting compact object that launches the jets; its mass; the main effect of the jets; resolved observed outcomes of the jets activity. Acronym: **BH**: black hole; **CCSNe**: core collapse supernovae; **CEE**: common envelope evolution; **CFs**: cooling flows; **GEE**: grazing envelope evolution; **ICM**: intra-cluster medium; **ILOT**: intermediate luminosity optical transient; **LBV**: luminous blue variable; **MS**: main sequence star; **NS**: neutron star; **PNe**: planetary nebulae; **SMBH**: super massive BH.

2 Inflating bubbles

Table 1 that is based on the one presented by Soker *et al.* (2013), presents the groups of objects that were claimed to have jet-inflated bubbles. Detail comparison of morphologies is conducted by Soker *et al.* (2013). The table is updated with the groups of grazing envelope evolution (GEE; Soker 2015), and that of intermediate luminosity optical transients (ILOTs) that were added by Kashi & Soker (2015) to the groups of objects where the JFM operates. In the GEE the jets launched by the companion are very efficient in removing the giant envelope gas, such that the companion never gets deep into the envelope. It can spirals-in, but no envelope will be left outside its orbit. It is possible that a GEE will turn to a common envelope evolution (CEE) if the jets do not manage to eject the envelope, and the companion spirals-in deep into the giant envelope. The suggestion that the JFM might operate in some ILOTs is based on the high-accretion-powered ILOT (HAPI) model (Kashi & Soker 2015). In the HAPI model it is assumed that ILOT events are powered by accretion of mass at a very high rate onto a main sequence (MS), or slightly evolved off the MS, star. In this short article I only mention the following in regards to Table 1.

Table 2. JFM properties and its fizzle outcomes

	Clusters CFs	Young galaxies	CCSNe	CEE[1][2]	GEE[1]	ILOTs[2]
Accretor	SMBH	SMBH	NS/BH	MS/WD/NS	MS/NS	MS
R_a (cm)	10^{13-16}	10^{11-14}	10^6	10^{11}	10^{11}	10^{11-12}
$\Phi_a\,(\mathrm{km/s})^2$	c^2	c^2	$(10^5)^2$	$(500)^2$	$(500)^2$	$(1000)^2$
$R_{\rm res}$ (cm)	10^{21-24}	10^{20-23}	10^9	10^{13}	10^{13}	10^{11-13}
$\Phi_{\rm res}\,(\mathrm{km/s})^2$	$(1000)^2$	$(300)^2$	$(10\,000)^2$	$(30)^2$	$(30)^2$	$(30-10^3)^2$
$\Phi_a/\Phi_{\rm res}$	$\approx 10^5$	$\approx 10^6$	≈ 100	≈ 100	≈ 100	$\approx 3-100$
Role of the JFM	Maintain ICM temperature	SMBH-bulge mass correlation	Explosion energy $\approx$ binding energy	Not much	Ensures outer envelope removal	Might limit accretion rate, but much above Eddington limit
Fizzle outcome	Cooling catastrophe	Rapid SMBH growth	BH formation; GRB	Core-secondary merger	Forming a common envelope	

The role of the jet feedback mechanism (JFM). R_a and Φ_a stand for the typical radius of the accretor, and the gravitational potential on its surface. $R_{\rm res}$ and $\Phi_{\rm res}$ stand for the typical radius of the reservoir of gas for accretion and the energy required to expel it from the system.

[1]We refer here only to a giant primary star (AGB, RGB, etc.)

[2]While in the other objects jets are crucial ingredient in the evolution, in the CEE and in ILOTs in some cases jets do not occur, or play a small role. As well, not in all cases the JFM operates even if jets do exist.

(1) *Observations.* Bubbles are clearly observed in cooling flows (CFs) in galaxies and in clusters of galaxies, in bipolar planetary nebulae (PNe), and in some ILOTs, such as the Great Eruption of η Car that formed the Homunculus in the 19$^{\rm th}$ century. As well, jets are known to be active in galaxy formation.

(2) *Expelling gas.* Jets are thought to expel gas in the process of galaxy formation. In some other cases jet-inflated bubbles are hypothesized to eject mass. In light of the failure of neutrino-based processes to explode massive stars, the jittering-jets model to explode massive stars as core collapse supernovae (CCSNe) was proposed. Jets are hypothesized to facilitate mass ejection in many cases of common envelope evolution (CEE). Jet are very efficient in expelling the giant envelope gas outside the secondary orbit in the GEE. While jets are crucial in CCSNe and in the GEE according to this picture, they are not mandatory in the CEE.

(3) *The JFM.* The JFM is a crucial in some systems, while in some systems, like the shaping of bipolar PNe by jets, the JFM does not operate. In the CEE and in ILOTs the JFM might act, but it does not have a crucial role. In galaxy formation (young galaxies), in CFs, and in CCSNe the JFM plays a crucial role. Table 2 lists the role of the JFM in the different systems. In shaping bipolar PNe it has no role, and hence bipolar PNe are not listed in Table 2. One should notice the difference between the role of the jets, as listed in Table 1, and the role of the JFM in regulating the activity cycle, the duration, and the power of the jets.

3 When the jet feedback mechanism fizzle

I discuss the outcomes when the JFM fizzle. One way by which the JFM can fail is if the jets are well collimated and preserve a non-variable axis, hence the jets interact with a small fraction of the reservoir gas along the polar directions; mass is continuously accreted from the equatorial plane. This is the case when the angular momentum of the accreted gas has a well-defined direction. The jets cannot stop the accretion even when their power increases.

In some systems the JFM is still a speculative process not in the consensus, and so the fizzle-outcomes in these systems will be speculative as well. These systems include the CEE, GEE and the jittering-jets model in CCSNe.

• *Clusters CFs.* When the AGN jets do not heat the ICM efficiently, a cooling catastrophe might occur. The ICM cools on its radiative cooling time, and leads to high rate star formation. Mass feeds the SMBH as well, and eventually energetic jets will heat the ICM to reestablish the JFM.

• *Young Galaxies.* The JFM can fail in preventing the growth of the SMBH if the accreted gas posses a well defined angular momentum axis over a long time. This might be the case in elliptical galaxies or bulges that posses fast and regular rotation. I suggest this explanation to the over-massive SMBHs in the galaxies MRK1216 and NGC1277 that have over-massive SMBHs and have fast and regular rotation (Yıldırım *et al.* 2015).

• *CCSNe.* The JFM mechanism can be inefficient in CCSNe when the pre-collapse core is rapidly rotating. In this case a well defined accretion disk is formed around the newly formed NS, and the jets have a well define propagation axis. The jets do not eject much of the core gas near the equatorial plane. A BH might formed that launches relativistic jets. This is the scenario for gamma ray bursts (GRB) in the jittering-jets model. Eventually the jets do remove large portion of the stellar mass, and a CCSN does take place in parallel to the GRB.

• *CEE.* Jets might not be necessary to eject the envelope in all CEE cases. In many cases where jets are not efficient, however, I speculate that merger of the secondary star with the core takes place. This might especially be the case with WD companions spiraling inside the envelope of a relatively massive giant, more than about $3M_\odot$. The merger product might be a Type Ia supernova progenitor according to the core-degenerate scenario.

• *GEE.* The GEE is based on efficient envelope gas removal by jets. This prevents the formation of a CE. When the jets fail in that, a CEE will commence.

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